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THE SPACE-CHARGE RESONANCE ACCELERATOR.(U)

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THE SPACE–CHARGE RESONANCE ACCELERATOR

BY HAN S. UHM
JOON Y. CHOE

RESEARCH AND TECHNOLOGY DEPARTMENT

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The space-charge resonance accelerator (SRA) consists of a relativistic electron beam propagating through a dielectric loaded drift tube. In a range of physical parameters, the phase velocity of a self-growing space-charge wave increases slowly from zero to a large beam velocity as it propagates into the downstream region, thereby trapping and accelerating ions by its electric field. The self-growing mechanism of the space-charge wave is a typical Cherenkov radiation.

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FOREWORD

The space-charge resonance accelerator (SRA) consists of a relativistic electron beam propagating through a dielectric loaded drift tube. In a range of physical parameters, the phase velocity of a self-growing space-charge wave increases slowly from zero to a large beam velocity as it propagates into the downstream region, thereby trapping and accelerating ions by its electric field. The self-growing mechanism of the space-charge wave is a typical Cherenkov radiation. This research was supported by the Independent Research Fund at the Naval Surface Weapons Center.

H. R. RIEDL
By direction

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ILLUSTRATIONS

In recent years, a number of collective ion acceleration methods with linear electron beams has been proposed and investigated at several laboratories.[1-5] One of the successful experiments in collective ion acceleration is the linear beam ion acceleration in an evacuated drift tube where ions are provided by an insulating material or a local gas puff.[4,5] In this paper, we present a new promising scheme to accelerate ions by utilizing relativistic electron beams. A schematic system configuration of the space-charge resonance accelerator (SRA) is presented in Fig. 1(a), where a relativistic electron beam with radius R_b enters into a cylindrical drift tube loaded with a dielectric material in the range $R_w < r < R_c$. The dielectric constant of the dielectric material is denoted by ε. A grounded cylindrical conducting wall is located at radius R_c, which in general is a function of the axial coordinate z. The electron energy at the anode is $\gamma_0 mc^2$ where m is the rest mass of electrons and c is the speed of light in *vacuo*. A reflex diode mesh is located at the position where the virtual cathode occurs. The drift tube length is denoted by L. A strong, externally applied magnetic field is needed to confine the beam electrons radially.

The formation of a virtual cathode downstream of the anode occurs where the injected electron beam current at the anode exceeds the limiting current for propagation of an electron beam, reflecting back most of

electrons at the reflex diode mesh. In this regard, only a small fraction of beam electrons can propagate further into the downstream region. The electric potential $\phi(r,z)$ in the drift tube can be self-consistently determined from the Poisson equation,

$$\left(\frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial}{\partial r} - \frac{\partial^2}{\partial z^2}\right)\phi(r,z) = - 4\pi\rho(r,z) \ , \qquad (1)$$

including influence of the geometric configuration. In Eq. (1), $\rho(r,z)$ is the charge density. However, calculation of the electric potential $\phi(r,z)$ is rather a formidable task. In this article, we therefore examine the essential properties of the electric potential in the limiting cases, leaving most of the work to future investigation. In the case when the potential variation in the axial direction is dominant (i.e., $|\partial\phi/\partial z| >> |\partial\phi/\partial r|$), Eq. (1) reduces to a one-dimensional Poisson equation which has been extensively investigated in the previous literatures.[5,6] Obviously, the distance L between the anode plane and the conducting plane at end of the drift tube plays a major role in the potential determination.

On the other hand, when the potential variation in the radial direction is dominant, Eq. (1) can be approximated by

$$\frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial}{\partial r}\phi(r) = \frac{4I}{R_b^2\beta c} U(R_b - r) \ , \qquad (2)$$

where I is the total current, βc is the axial velocity of electrons at axis and U(x) is the Heaviside step function. In obtaining Eq. (2), we assume that the current density is uniform over the beam cross section consistent with a thin beam. Defining $\phi_0 = \phi(r = 0)$ and making use of the identity $\gamma = \gamma_0 + e\phi_0/mc^2$, where γmc^2 is the electron energy at axis and $-e$ is the electron charge, it is straightforward to show

$$f(\gamma) \equiv \frac{(\gamma^2 - 1)(\gamma - \gamma_0)^2}{\gamma^2} = \left(\frac{eI}{mc^3}\right)^2 \left\{1 + 2\left[\ell n\left(\frac{R_c}{R_b}\right) - \frac{\varepsilon - 1}{\varepsilon}\, \ell n\left(\frac{R_c}{R_w}\right)\right]\right\} \tag{3}$$

After a careful examination of Eq. (3), we find that the function $f(\gamma)$ increases from zero to its maximum value $(\gamma_0^{2/3} - 1)^3$ as the γ value decreases from $\gamma = \gamma_0$ to $\gamma = \gamma_0^{1/3}$. In this context, the maximum current (or limiting current) can be expressed as

$$I_{max} = \frac{(mc^3/e)(\gamma_0^{2/3} - 1)^{3/2}}{1 + 2[\ell n(R_c/R_b) - (\varepsilon - 1)\ell n(R_c/R_w)/\varepsilon]} . \tag{4}$$

From Eq. (3), it is found that the axial velocity βc of electrons is an increasing function of the dielectric constant ε and the ratio R_c/R_w. Moreover, Eq. (4) is identical to the result obtained by Bogdankevich and Rukhadze[7] in the limit of $\varepsilon = 1$ or $R_w/R_c = 1$. Apparently, the electric potential profile is determined from the combination of these two extreme cases. Shown in Fig. 1(b) is a schematic plot of the normalized potential $e\phi_0(z)/mc^2$ versus z. It is worthy to note from Fig. 1(b) that the axial velocity βc of electrons is monotonically increasing from zero to $(\gamma_0^2 - 1)^{1/2}c/\gamma_0$ as the electrons move from the location of the reflex diode mesh to $z = L$. In general, the velocity profile $\beta(z)c$ is described in terms of the parameters L, ε, and R_w/R_c.

It has been shown in the previous study[8] that the slow space-charge wave couples with the transverse magnetic (TM) dielectric waveguide mode, exhibiting a strong instability. The physical mechanism of instability is the well-known Cherenkov radiation. In an unstable range of physical parameters, amplitude of the slow space-charge wave grows as it propagates into the downstream region [see Fig. 1(c)]. The TM dielectric waveguide mode is obtained from the differential equation

$$\left(\frac{1}{r} \frac{\partial}{\partial r} r \frac{\partial}{\partial r} + p^2 \right) \delta E_z(r) = 0 \ , \qquad (5)$$

where δE_z is the axial component of the electric waveguide field, and $p^2 = \omega^2 \varepsilon/c^2 - k^2$ for $R_w < r < R_c$ and $p^2 = \omega^2/c^2 - k^2$ for $0 \leq r < R_w$, ω is the eigenfrequency and k is the axial wavenumber. In general, solutions to Eq. (5) are a linear combination of Bessel functions of the first kind $J_\ell(x)$ and second kind $N_\ell(x)$ of order ℓ. After a straightforward algebra, we obtain the TM dielectric waveguide mode,

$$\frac{\xi J_0(\xi)}{J_1(\xi)} = \frac{\eta}{\varepsilon} \frac{J_0(\eta)N_0(\zeta) - J_0(\zeta)N_0(\eta)}{J_1(\eta)N_0(\zeta) - J_0(\zeta)N_1(\eta)} \ , \qquad (6)$$

where the parameters ξ, η, and ζ are defined by $\omega^2/c^2 - k^2 = \xi^2/R_w^2$, $\omega^2 \varepsilon/c^2 - k^2 = \eta^2/R_w^2$ and $\zeta = \eta R_c/R_w$.

Maximum coupling of the space-charge wave and the dielectric waveguide mode occurs near the intersecting point of the free-streaming mode,

$$\omega = k\beta c \ , \qquad (7)$$

with the waveguide mode in Eq. (6). In order for a steady growth of the space-charge wave, it is necessary to find the conditions for the maximum coupling. Solving simultaneously Eqs. (6) and (7) for a broad range of physical parameters, we present in Fig. 2 plots of the beam velocity βc versus R_w/R_c corresponding to the maximum coupling for $(\omega R_w/c)^2 = 1$ and 4, and several different values of the dielectric constant ε. For $R_w/R_c << 1$, Eq. (6) can be approximated by $\omega^2 \varepsilon/c^2 - k^2 = \beta_{01}^2/R_c^2$ where β_{01} is the first root of $J_0(\beta_{01}) = 0$. Therefore, the maximum coupling condition is given by,

$$\beta = [\varepsilon - \beta_{01}^2/(\omega R_c/c)^2]^{-1/2} \ , \qquad (8)$$

which agrees excellently with the plots in Fig. 2 for $R_w/R_c \lesssim 0.4$. Velocity of the electron beam after the reflex diode increases as it propagates further into the downstream region. In this regard, for specified values of $\omega R_w/c$ and ε, contouring the conducting wall according to Fig. 2 gives a maximum growth of the space-charge wave all the way through the downstream region. On the other hand, we note from Fig. 2 that the maximum growth can also be attainable by changing the dielectric constant ε along the z-direction instead of contouring of the wall.

Finally, the phase velocity ω/k for the slow space-charge wave is determined from[8]

$$\left(\frac{k\beta c}{\omega} - 1\right)^2 = \frac{4\nu}{\gamma^3} \frac{1 - \left(\frac{\omega}{kc}\right)^2}{\left(\frac{\omega g_f}{kc}\right)^2 + \left(\frac{\omega R_b}{c}\right)^2 \left(1 - \frac{\omega^2}{k^2 c^2}\right)} , \tag{9}$$

where $\nu = N_b e^2/mc^2$ is Budker's parameter of the beam, g_f is a geometric factor of order unity, and N_b is the number of electrons per unit axial length. Note that N_b has a maximum value near the reflex diode and decreases as the beam propagates further into the downstream region. In this regard, even for a small Budker's parameter averaged over the entire beam in the drift tube, the local value of Budker's parameter near the reflex diode can be very large.

For a small beam velocity ($\beta << 1$), corresponding to the beam segment right after the reflex diode in Fig. 1(a), Eq. (9) can be approximated by

$$\omega/kc \simeq \beta[1 + 2(c/\omega R_b)\nu^{1/2}]^{-1} , \tag{10}$$

indicating that the phase velocity of the space-charge wave is a

small fraction of the beam velocity for Budker's parameter order unity. For example, for $\beta = 0.2$, $R_b\omega/c = 0.5$ and $\nu = 1$, the phase velocity of the space-charge wave is given by $\omega/kc = 0.04$ which is already sufficiently small to initially trap and accelerate ions. However, we note from Eq. (9) that the phase velocity of the space-charge wave approaches to the beam velocity as β increases to unity, clearly indicating advantages in the collective ion acceleration. Ions, initially trapped near the reflex diode by the space-charge wave, are further accelerated by the wave electric field. In order to achieve a maximum ion acceleration, the ion velocity is synchronized with the phase velocity of the space charge wave. Meanwhile, the amplitude of the space-charge wave is steadily growing by the instability mechanism, providing a necessary energy for ion acceleration. Initial perturbation of the space-charge wave may be the electron beam noise near the reflex diode mesh.

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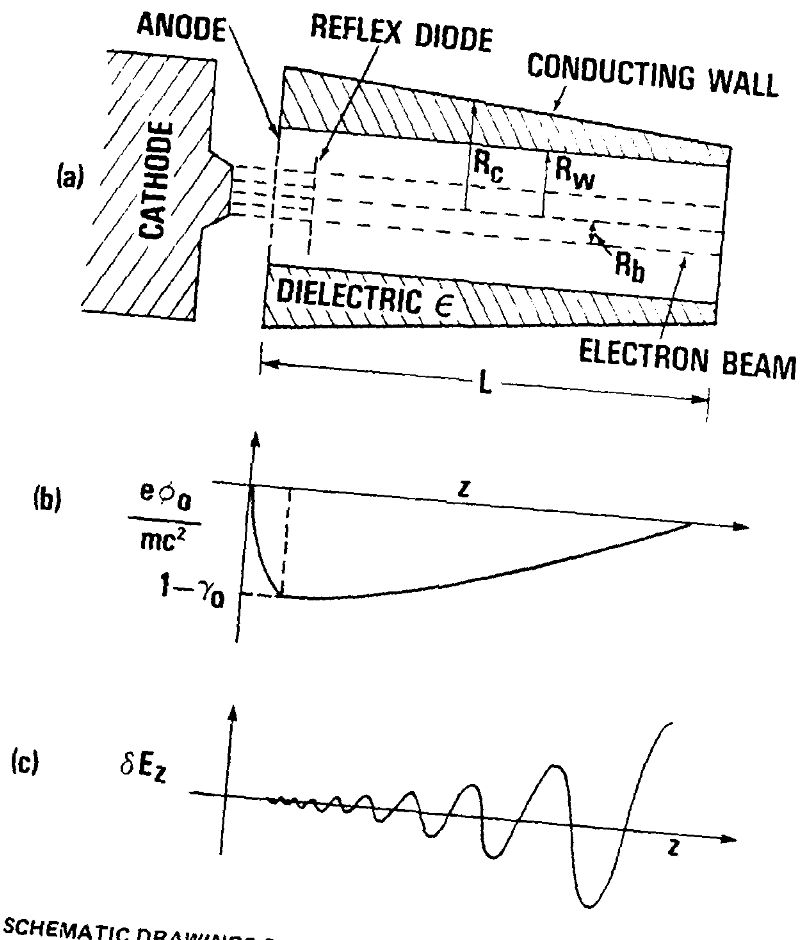

FIGURE 1 SCHEMATIC DRAWINGS OF THE SPACE-CHARGE RESONANCE ACCELERATOR: (a) SYSTEM CONFIGURATION, (b) PLOT OF THE NORMALIZED POTENTIAL VERSUS Z, (c) GROWTH OF THE SPACE-CHARGE WAVE BY INSTABILITY MECHANISM.

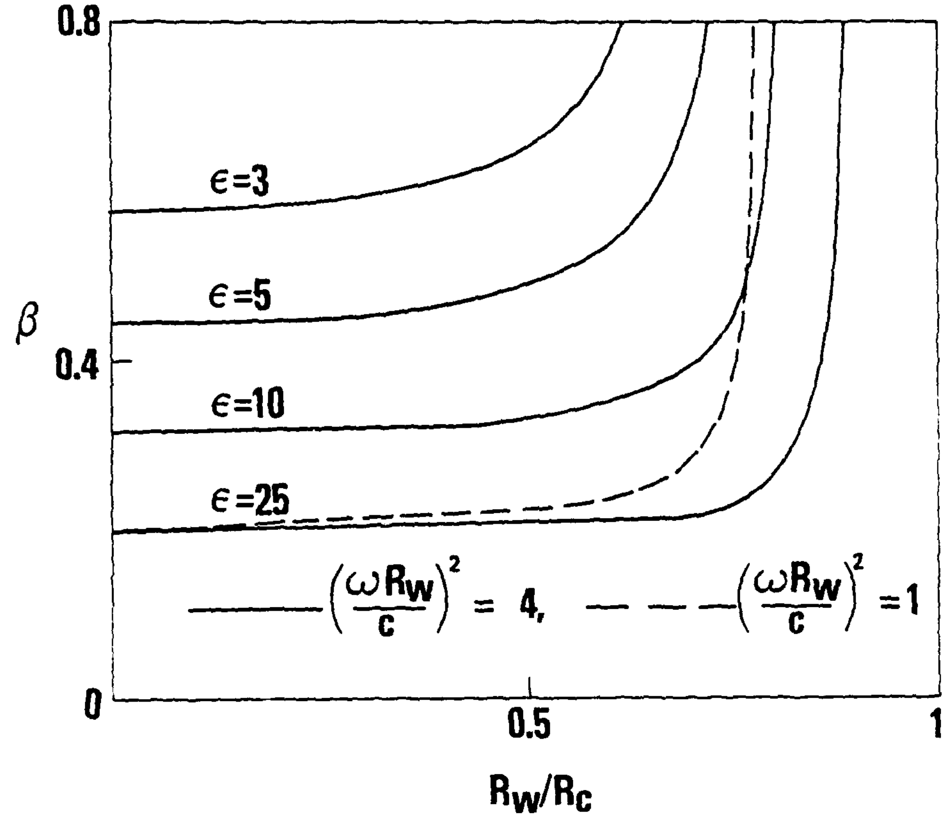

FIGURE 2 PLOTS OF THE BEAM VELOCITY βc VERSUS R_w/R_c CORRESPONDING TO THE MAXIMUM COUPLING FOR $(\omega R_w/c)^2 = 1$ AND 4 AND SEVERAL DIFFERENT VALUES OF DIELECTRIC CONSTANT ϵ.

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